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NASA LCLUC Program

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**Spatial Predictive Modeling and Remote Sensing of
Land Use Change in the Chesapeake Bay Watershed**

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I. Overview

This project was focused on modeling the processes by which increasing demand for developed land uses, brought about by changes in the regional economy and the socio-demographics of the region, are translated into a changing spatial pattern of land use. Our study focused on a portion of the Chesapeake Bay Watershed where the spatial patterns of sprawl represent a set of conditions generally prevalent in much of the U.S. Working in the region permitted us access to (i) a time-series of multi-scale and multi-temporal (including historical) satellite imagery and (ii) an established network of collaborating partners and agencies willing to share resources and to utilize developed techniques and model results. In addition, a unique parcel-level tax assessment database and linked parcel boundary maps exists for two counties in the Maryland portion of this region that made it possible to establish a historical cross-section time-series database of parcel level development decisions. Scenario analyses of future land use dynamics provided critical quantitative insight into the impact of alternative land management and policy decisions. These also have been specifically aimed at addressing growth control policies aimed at curbing exurban (sprawl) development. Our initial technical approach included three components: (i) spatial econometric modeling of the development decision, (ii) remote sensing of suburban change and residential land use density, including comparisons of past change from Landsat analyses and more traditional sources, and (iii) linkages between the two through variable initialization and supplementation of parcel level data. To these we added a fourth component, (iv) cellular automata modeling of urbanization, which proved to be a valuable addition to the project.

II. Questions, Goals, Approaches

Science Questions

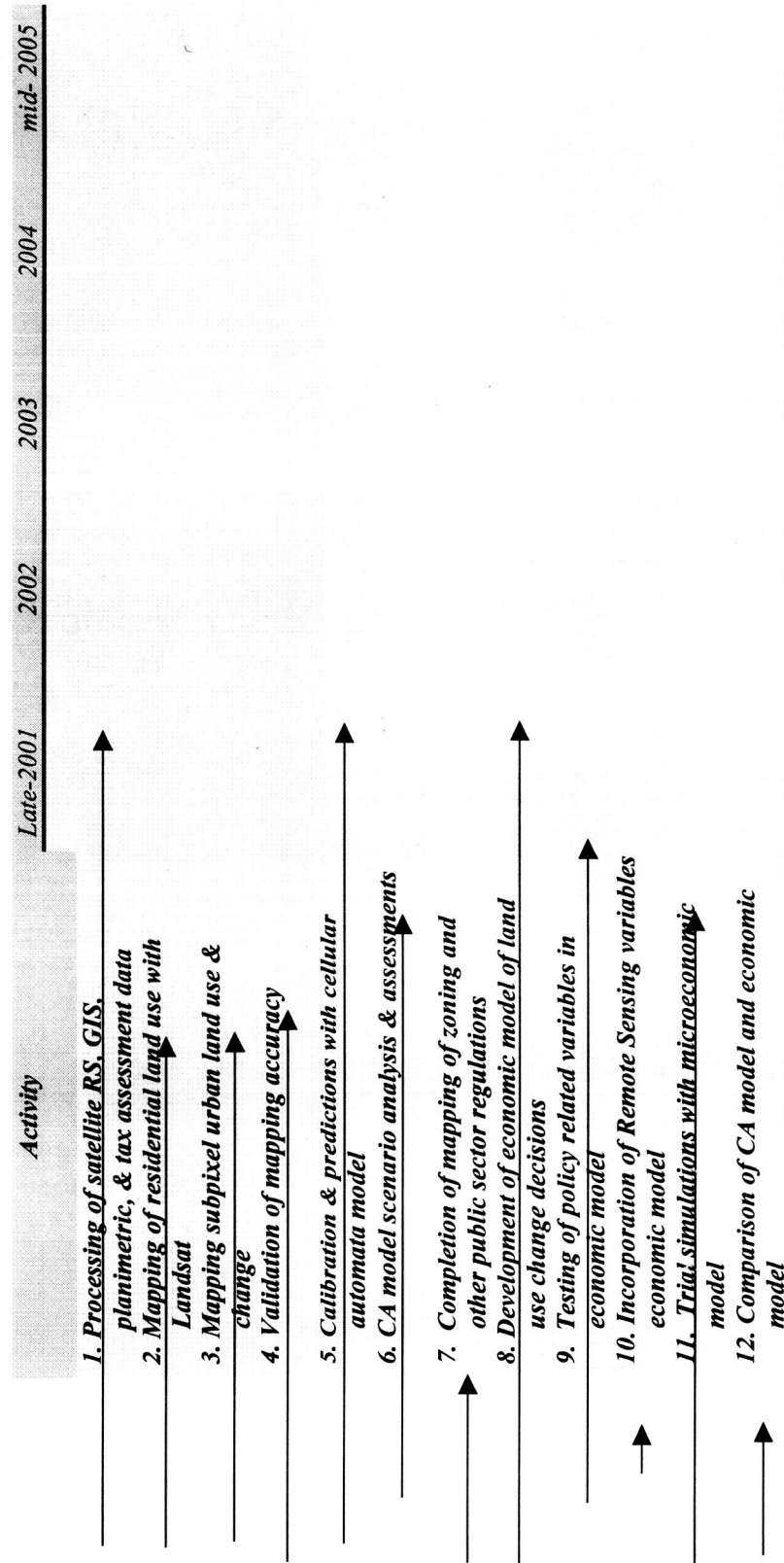
Our research project incorporated a number of the NASA LCLUC program's stated research priorities, including socioeconomic "drivers" as *forcing factors* of land use change, land cover conversion and land-use intensification as *responses and consequences* of land use change, agent-based models as simulators of the *processes and implications* of land use change, and multi-sensor remote sensing as part of the *techniques and methods* to monitor land use change. Our work addressed mapping and monitoring urbanization in the study region using innovative remote sensing techniques while also, from a completely different perspective, spatially modeling the land use change decision at the pixel (cell) and the individual property owner level. Later stages of the project, which we continue to address through related work, considers the linkages between these approaches, and consequences of the observed and predicted changes. We attributed the following emphases to the NASA LCLUC focus areas:

- Social science (50%), Remote sensing research and applications (50%)
- GOF themes (50%), Socioeconomics (50%)

Goals & Timelines

The timelines generally followed those as initially laid out in the proposal (Figure 1), although over a longer time period due to PI Goetz's move from the UMD to WHRC.

Figure 1. Project timelines Sept 2001- July 2005



II. Results and Findings

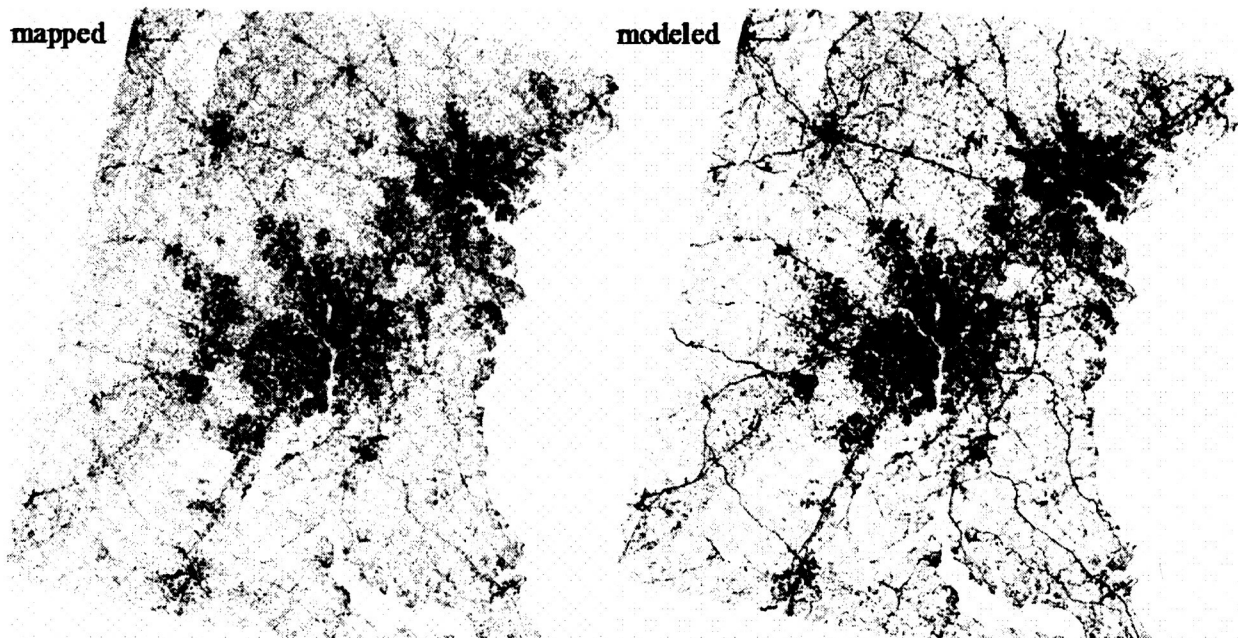
Monitoring Urbanization with Satellite Remote Sensing

A series of classifications were developed to test the capability of Landsat imagery for mapping various densities of impervious surface areas (ISA) and residential land use, based on classification and regression tree (CART) algorithms. In the case of ISA, we found the subpixel mapping algorithms to be highly accurate¹, and useful for testing various land use policy scenarios². In the case of residential density mapping, the accuracies were lower, particularly errors associated with low-density areas³. It was possible to separate residential areas from commercial / industrial and agriculture, to some extent, but difficulties arose in the discrimination of low-density areas due to the range of land cover types within this specific land use, and their associated spatial variability. For this reason we focused primarily on the use of ISA maps for incorporation with the predictive modeling aspects of the project. We summarized this aspect of the work as a contribution to the NASA LCLUC "Land Change Science" book⁴.

Modeling Urbanization using Cellular Automata

The cellular automaton (CA) approach to modeling urban dynamics, based on the SLEUTH model, was used to simulate urban development patterns in the Washington, DC-Baltimore, MD metropolitan area², following calibration with the series of past urban extent maps derived from Landsat imagery^{1,4}. We found that SLEUTH captured the historic rate of development and successfully replicated the spatial patterns of historical development (Figure 2), although the model was sensitive to scale (grain size)⁵. We produced maps of future urban extent suitable for visualizing future land uses (see attached NASA lithograph), and designed policies to address areas at most risk of change (Figure 3).

Figure 2. *Sleuth model calibration: urban extent as of the year 2000 in the greater Washington DC metropolitan area compared to that modeled from 1986 to 2000..*



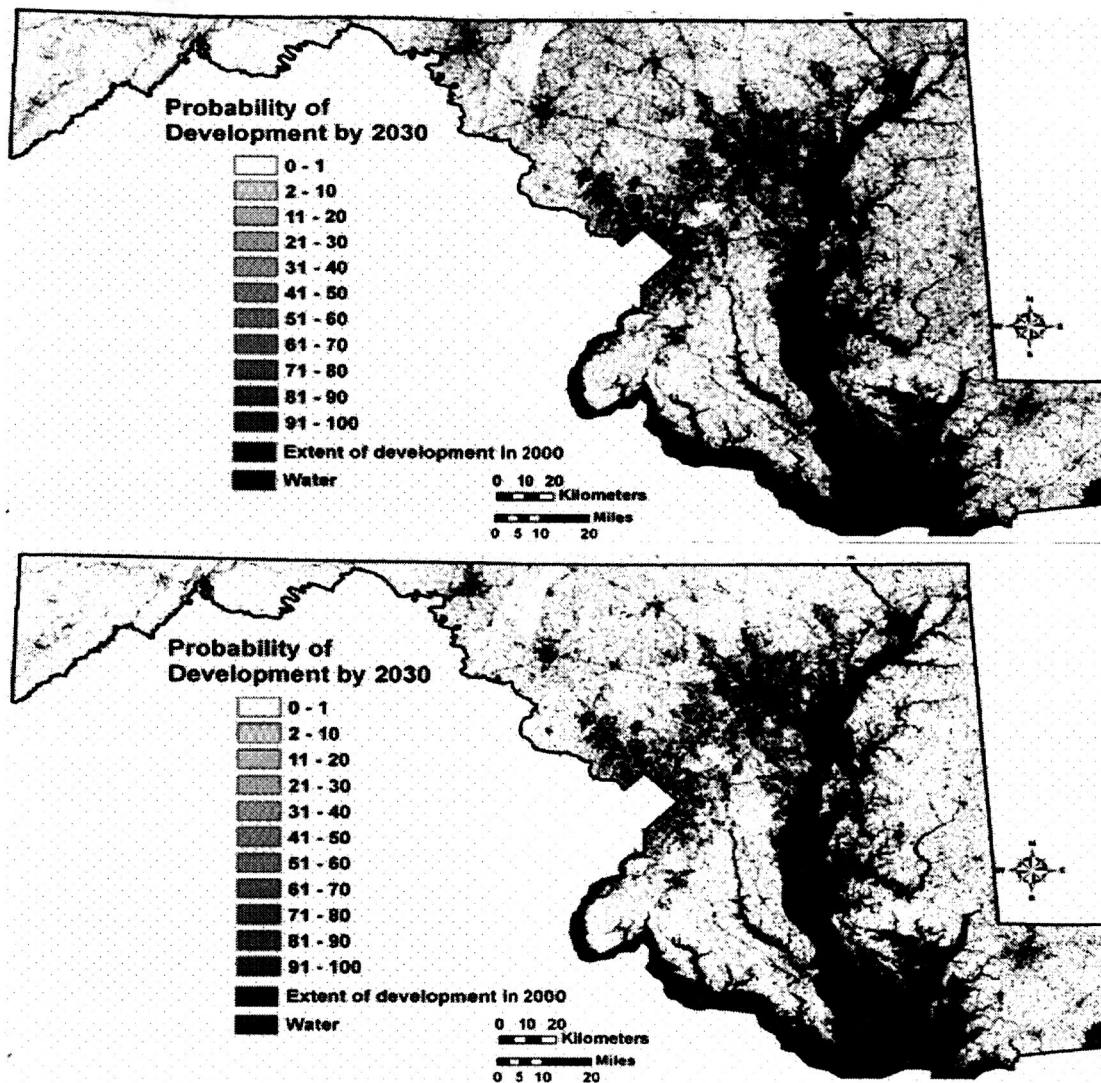


Figure 3. Urban extent across the state of Maryland modeled using Sleuth to the year 2030 under “current trends” (top) and “managed growth” scenarios.

Modeling Development using an Economic & Parcel-Based Approach

In parallel to the CA modeling, co-PI Bockstael utilized a statistical modeling approach based on the economic theory of land use change decision-making at the parcel level⁶⁻⁹. In last year of the project, in particular, the empirical model was revised to be consistent with ‘real options’ theories of investment decision making. This improvement provided a more rigorous and defensible theoretical underpinning to the empirical work, allowed the incorporation of direct feedback of price signals from land and housing markets, and was consistent with the empirically observed phenomenon that parcels are not developed as soon as the development option becomes profitable. It also explains how the decision process changes when land owners face the alternative options of development or preservation.

In order to estimate the parameters in the empirical model, historical cross-sectional, time-series data on past land use conversion decisions at the parcel level were combined with characteristics of all developable parcels to statistically “explain” the relationship between parcel characteristics and likelihood of conversion. The mapping of zoning, public sector regulations, and other important public goods (e.g. school districts and quality) was input to the EC model. The analytical process incorporated factors such as commuting distances, parcel size, number and size of lots that can be developed from a parcel (according to zoning), environmental restrictions, provision of public utilities, access to public goods (such as parks, schools of different quality, etc), topography, impact fees and property taxes, value of land in non-developed use (e.g. agricultural productivity), and surrounding land use.

The model itself considers the decision of whether and when to develop (or further develop) a parcel that, given existing regulations and parcel characteristics, can be developed. It also attempts to explain the alternative decision to sell the rights to develop and therefore preserve the parcel in publicly available open space preservation programs. The analysis incorporates specific growth control regulations such as adequate public facilities moratoria, priority funding areas, provision of public utilities, clustering regulations, etc. It does so in terms of the way these regulations alter the factors that make development more or less profitable. This is important because many growth controls operate by providing incentives or disincentives rather than outright prohibitions on development. The analysis tests for significant effects of these factors and produces quantitative estimates of these effects on the probabilities of development. By understanding how regulations affect profitability of development and how this profitability alters likelihood of development, the mechanistic approach allows us to evaluate the effects of proposed (and as yet unimplemented) changes in regulations.

The type of statistical analysis used is hazard (or survival/duration) analysis. Once the parameters of the hazard models are estimated, it is possible to use these parameters to predict the timing of development decisions. The nature of the results are, however, probabilistic. In the last year of the project we have developed algorithms to generate multiple realizations of outcomes, where each is a random draw from the underlying predicted probability distributions. This allows us to generate predicted output from the economic model that matches the form of output that cellular automata models provide.

One important feature of our work is the incorporation of exogenous landscape attributes measured by remote sensing into the parcel-based EC modeling. The most useful factors were the types of land cover describing the original developable parcel and the nature of land cover surrounding a developable parcel. Both agricultural cropping patterns and impervious surface measures gathered from the remote sensing work contributed in an important way. Results suggest that surrounding land use/land cover has significant impacts on the likelihood of development or preservation, and we were able to generate estimates of their quantitative effects. Measuring the effects of policies on development requires careful statistical analysis, because factors increasing the likelihood of development in an area often also increase the likelihood that a particular policy will be applied to that area. It is therefore difficult to statistically ‘identify’ causation. Failing to do so causes bias in estimated parameters and incorrect deductions about policy effectiveness. Specific problems being addressed relate to measuring the effect of the Priority Funding Areas, adequate public facilities moratoria, and publicly preserved open space

on the likelihood of development of neighboring parcels. These types of influences are not addressed in the CA modeling approach, which is a spatial pattern and rate of change replication model manipulated by GIS layers identifying exclusion probabilities (i.e., a suitability surface).

Comparing Modeling Approaches

The distinctions between these two types of modeling approaches (parcel –vs– cell based) are important for simulating the land use change process and addressing the influence of policy decisions. The fundamental differences between the two approaches are summarized in Table 1. The cellular automata (CA) model is aimed at mimicking past patterns of land use and land use change, while the economic (EC) model attempts to model the human decision process that causes that change. The CA model operates at the level of a map pixel, while the unit of observation in the EC model is the privately owned parcel. The difference in the nature of predictions resulting from difference in the basic unit of observation is illustrated graphically in Figure 4, using an example from Montgomery County, MD. The CA model does not incorporate the immense detail of the EC model and the spatial pattern of development predicted by the two models is quite different.

The CA model has the overall advantage of far easier and more generalizable application. However, modifications necessary to introduce more realistic and regional-specific detail reduce this advantage somewhat. In addition, because it is not based on modeling the actual mechanistic behavior of decision makers, it is incapable of distinguishing between factors that actually cause different outcomes and factors that are highly correlated with different outcomes. The EC model has the advantage of being mechanistic, capturing elements of the complex decision environment and including institutional information that varies geographically and feedbacks from the regional market. Because it is based on explaining the process, it can be used to distinguish between causation and correlation. The EC model also has the further advantage of being able to better predict future outcomes under changes in existing policies or introduction of new regulations because this model better explains the nature of decision making in a constrained environment⁶⁻⁹. We are preparing a publication on these model comparisons.

Table 1: Comparison of modeling approaches

	Cellular automaton modeling	Economic modeling of the development decision
Unit of observation	Cell in landscape	Privately owned parcel of land
Nature of approach	Pattern-based	Process-based
Nature of land use change processes	Stochastic process regulated by conceptually simple transition rules. SLEUTH employs rules that model slope resistance, edge growth, dispersed growth, new spreading center growth and road-influenced growth.	Stochastic model of behavior of land owners, who choose the optimal timing (in an economic sense) of development and optimal density of development.
“Driving forces”	State of current land cover, physical features of the landscape, user-defined areas that are protected from development	Value of land in undeveloped use and developed uses, and conversion costs. All are functions of: current land cover, physical and location features of parcel, public goods provision, and relevant regulations.
Analytical methods	Cellular automaton model that simulates cell changes using growth coefficients derived from an iterative calibration process based on observed cell changes.	Discrete choice or hazard model analysis to test hypotheses and calibrate parameter estimates for forecasting.
Data requirements	Urban extent data for at least four points in time; road networks for two points in time; slope; excluded layers for calibration and predictive scenarios.	Parcel level data, including locations of parcels, GIS data on physical features, regulations, public goods, land cover.
Source of growth pressure information	Historic rates and patterns of development.	Model of housing starts as a function of regional economic projections.

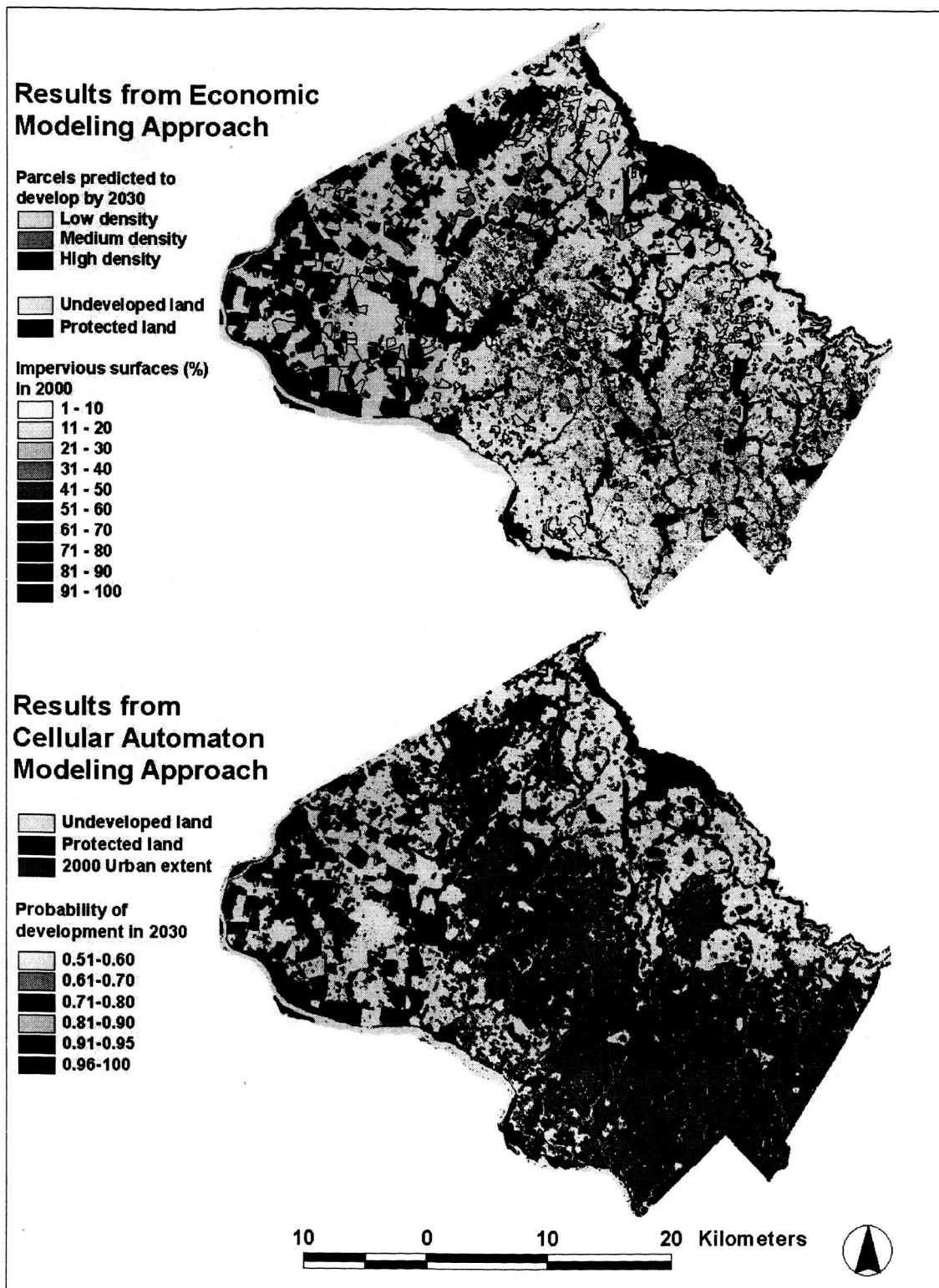


Figure 4: Comparison of predictive results from the economic modeling approach (upper graphic) and cellular automaton approach (lower graphic) for Montgomery County, MD.

Conclusion

This project has generated both remote sensing and spatially explicit socio-economic data to estimate and calibrate the parameters for two different types of land use change models and has undertaken analyses of these models. One (the CA model) is driven largely by observations on past patterns of land use change, while the other (the EC model) is driven by mechanisms of the land use change decision at the parcel level. Our project may be the first serious attempt at developing both types of models for the same area, using as much common data as possible. We have identified the strengths and weaknesses of the two approaches and plan to continue to revise each model in the light of new data and new lessons learned through continued collaboration.

Findings & Potential

- A CA model capable of predicting future urban land use change, calibrated at fine resolution using historical maps based on satellite imagery.
- Behavior of the CA model is impacted by the scale, or resolution, at which the urban system is represented; this influences the simulation of urban settlement patterns (e.g. low density residential development) across scales.
- Genetic algorithms can be used to speed the CA model calibration efficiency.
- A model based on economic theory of human decisions and government policies can be augmented to incorporate land cover information derived from satellite remote sensing observations.
- Integration of remote sensing variables into the economic model improves estimation of parameters that affect the likelihoods of development. This involves inclusion of impervious surface and tree canopy information as measures of surrounding land use and agricultural cropping information to help refine data on value of parcels in non-developed use.
- Statistical identification problems emerge in estimating the effect of growth control policies on development likelihoods, and efforts to correct for this suggest that these growth control policies may have some unintended outcomes.
- Comparison of CA and EC model predictions and analysis of model constraints indicate that modeling approaches can be augmented based on joint lessons learned from each.
- Implementation of a new method for translating predicted probabilities of development into useful simulation output can be used to more accurately compare CA and EC model output.
- Modifications to the CA model, and manipulation of 'parameter sets' by incorporating "rules" from the economic model, can be used to improve CA model performance – especially in capturing low-density residential development.

Publications:

- 1) Jantz P., S. J. Goetz & C. A. Jantz (2005), Urbanization and the loss of resource lands within the Chesapeake Bay watershed. *Environmental Management*, in press.
- 2) Jantz, C. A., S. J. Goetz, and M. A. Shelley (2003), Using the SLEUTH urban growth model to simulate the land use impacts of policy scenarios in the Baltimore-Washington metropolitan region. *Environment and Planning B* 31(2): 251-271.
- 3) McCauley, S., and S. J. Goetz (2004), Mapping residential density patterns using multi-temporal Landsat imagery and a decision-tree classifier. *International Journal of Remote Sensing* 25(6) : 1077-1094.
- 4) Elvidge C., Sutton P. C., Wagner T. W., Vogelmann J. E., Goetz S. J., Smith A. J., Jantz C., Seto K. C., Imhoff M. L., Wang Y. Q., Milesi C. & Nemani R. (2004) Chapter 18: Urbanization. In: *Land Change Science: Observing, Monitoring, and Understanding Trajectories of Change on the Earth's Surface* (ed. Gutman) pp. 315-328. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- 5) Jantz, C., and S. J. Goetz. (2005) *Analysis of scale dependencies in an urban land use change model*. *International Journal of Geographic Information Systems* 19(2):217-241.
- 6) Irwin, E. and N. Bockstael (2005), Endogenous spatial externalities: empirical evidence and implications for exurban residential land use patterns. *Advances in Spatial Econometrics, Methodology, Tools and Applications* (ed. Anselin, Florax and Rey), Springer-Verlag, in press.
- 7) Irwin, E. and N. Bockstael (2005), Patterns of Urban Land Use. *A Companion to Urban Economics* (eds. Arnott and McMillen), Blackwell Publishing, in press.
- 8) Irwin, E. and N. Bockstael (2004), Land use externalities, open space preservation, and urban sprawl. *Regional Science and Urban Economics*, 34(6): 705-725.
- 9) Bockstael, N. and E. Irwin (2003), Public policy and the changing landscape. *Estuaries*, 26(2A), pp 210-225.

Oral presentations:

- Sept 2002, *Mapping and Predicting Land Use Change within the Chesapeake Bay Watershed*, Chesapeake Bay Watershed Restoration Conference, Baltimore MD
- June 2002, World Congress of Environmental Economists, *Urban Sprawl as a Spatial Economic Process*, Monterey, CA.
- July 2002, Lincoln Land Institute, *Urban Sprawl as a Spatial Economic Process*, Boston, MA.
- April 2003, Framing Land Use Dynamics, (i) *Linking land use change in the built environment to watershed health*, and (ii) *Modeling future land use change in the Baltimore-Washington DC area*, Utrecht Netherlands
- April 2003, Boston University Geography Dept Seminar Series, *Remote sensing applications within the Chesapeake Bay Watershed*, Boston MA.

- May 2003, EPA ReVA-MAIA Conference: Using Science to Assess Environmental Vulnerabilities, *Assessing the Vulnerability of Resource Lands in the Chesapeake Bay Watershed*, King of Prussia, PA
- June 2003, Association of Environmental and Resource Economists, *Testing for the effect of growth control measures using quasi-experimental design*, Madison, WI.
- July 2003 Lincoln Institute of Land Policy Workshop, *Managing urban sprawl*, Cambridge, MA.
- July 2003 2nd International Workshop on the Analysis of Multi-Temporal Remote Sensing Images, *Application of multitemporal Landsat data to map and monitor land cover and land use change in the Chesapeake Bay watershed*, Baltimore MD
- July 2003, International Geoscience and Remote Sensing Symposium (IGARSS), *Monitoring and modeling urban land use change using multi-temporal satellite data*, Toulouse France.
- August 2004, Society for Conservation Biology Annual Conference, *Exurban Sprawl, the Loss of Resource Lands, and Forest Vulnerability within the Chesapeake Bay Watershed*, New York City.
- Jan 2005, University of Massachusetts Boston, Environmental, Earth and Ocean Sciences Department, *Monitoring resource lands in the Chesapeake Bay watershed using satellite remote sensing*, Seminar Series, Boston, MA.
- Feb 2005, Brown University, Department of Environmental Sciences and Geology, *Land use change and stream health in the Chesapeake Bay watershed*, Seminar Series, Providence, RI.
- March 2005, Marine Biological Laboratory Seminar Series, *Land use change and loss of resource lands in the mid-Atlantic region using satellite remote sensing*, Woods Hole, MA.
- Aug 2005, American Agricultural Economics Association, *An Empirical Examination of Real Options and the Timing of Land Conversions*, Providence, RI.